HIGH ENERGY EMISSION FROM GALACTIC BLACK HOLE SYSTEMS

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In the last decade our knowledge on galactic black hole systems and in particular on their high energy behavior has considerably improved. I will briefly review here the main results obtained by the high-energy missions SIGMA/GRANAT, Compton-GRO, Beppo-SAX and Rossi-XTE, on these objects and, in particular, I will discuss the spectral shapes observed at energies higher than 30 keV and the detections of high energy features at > 300 keV. Galactic black holes are indeed main targets for the ESA gamma-ray mission, INTEGRAL, to be launched in October 2002, and for the next gamma-ray missions SWIFT, AGILE and GLAST. We expect that a large amount of data will be collected in the next years and the perspectives for the high energy astrophysics of galactic black hole systems look very promising.

1 Black Holes in Accreting Binary Systems

Our Galaxy probably hosts a large number of black holes (BH) of stellar mass sizes. Black holes, by definition, are difficult to observe, unless they are associated to a normal star in a close binary system. When in such a binary system transfer of matter occurs from the companion star to the black hole, the system may become a powerful source of X-rays. In the last 12 years (1990-2002) our knowledge of galactic black hole binary systems has increased enormously thanks to the large amount of results obtained in the standard X-ray band with Ginga, Rosat, ASCA, and now Chandra and XMM-Newton, and in the hard X-ray and gamma-ray range with SIGMA/GRANAT, Compton-GRO, Beppo-SAX and Rossi-XTE. Observations have shown that X-ray sources which seem associated to black holes in binary systems are very hard sources and infact often appear the brightest objects at energies between 10 keV - 1 MeV. They are also often observed to emit radiowaves and some of them, the so called *microquasars*, have been associated to radio-jet sources (Mirabel & Rodriguez 1999).

These systems are powered by accretion of matter provided by the companion star, which releases, by falling into the deep potential well of the hole, gravitational energy in form of high energy radiation. These systems are classified as high mass X-ray binaries (HMXB), when the star is young, massive (> 1 M$_\odot$), of early spectral type (O, B), or as low mass binaries (LMXB), when the secondary is old, of low mass (< 1 M$_\odot$), and of late spectral type (later than A). HMXB are generally large systems with orbital periods $P_o > 5$ days and the accretion usually occurs by the capture of the material from the strong stellar wind of the companion. It is not always clear whether a disk forms. In the small, low period LMXB ($P_o \approx$ few hr - 10 days), instead, the secondary fills the Roche lobe and matter is accreted with large angular momentum, often through an accretion disk.

All these objects are variable but some are visible most of the time (*persistent sources*) while others rather spend most of their life in a quiescence state, where they are very faint and even undetectable (*transient sources*). Obviously the classification depends slightly on the level of instrument sensitivity and the boundary between persistent and transient systems is somehow arbitrary. Some transients may reach a state where they are active for long time displaying erratic flux variability (e.g. GRS 1915+105) and some persistent sources may pass large period in very low states (e.g. GRS 1758-258, GX 339-4).

Transients are particularly interesting because during their quiescence period, their mass function can be measured in detail. Optical and infrared (IR) spectro-fotometry observations of binary systems in suitable conditions can provide radial velocity measures of the secondary orbital motion, which allows determination of the mass function of the system. We presently know 14 binary systems in our Galaxy and in the Magellanic Clouds, whose compact object mass has been determined (or constrained) and results larger than 3 $M_\odot$, the theoretical mass limit of a stable neutron star (NS), implying the presence of a black hole. Out of these dynamically proven BH, 3 are HMXB, the persistent sources Cyg X−1, LMC X-1, LMC X-3, the rest are all X-ray Novae. X-Ray Novae (XN), also known as Soft X-ray Transients, are LMXB normally in quiescence state, which undergo sudden few-month-long X-ray outbursts with typical recurrent times of few tens of years (Tanaka & Shibazaki 96). After the flare the systems generally return to the quiescence phase, the disk contribution to optical and IR emisson is reduced and the companion (identified during the outburst) can be studied in detail. That is why many XN have known mass functions and most of them are found to harbour a black hole as primary compact object. The most recent determination of a GBH mass is the one for GRS 1915+105 the first discovered superluminal microquasar, which contains the most massive BH ($\approx$ 14 $M_\odot$) of the known GBH (Greiner et al. 2001).

When the mass function cannot be determined, X-ray sources can be identified as BH candidate systems on the basis of their X-ray and gamma-ray spectral and variability properties. In particular the lack of distinctive signs of NS system variability (coherent pulsation, type I and II X-ray bursts) and the presence of a strong hard spectral component extending in the range $>$ 30 keV (plus signs of fast variability and variable ultrasoft component) are used to search for BH candidates. Several X-ray sources identified as BH candidates using a spectral criterium were later confirmed as BH systems from mass function measures. About 15 sources are considered today on these basis very serious BH candidates. Three of them are persistent sources, the variable source GX 339-4 and the two microquasars of the Galactic Center region 1E 1740.7-2942 and GRS 1758-258, probably LMXB for which no optical counterpart has been found. The others are member of the X-ray novae class.

2 High Energy Spectra of GBH

The prototype of the GBH class is the persistent, very bright and well known source Cyg X−1. It is a HMXB with a P_o of 5.6 days, a O9.7 Iab companion and an estimated BH mass of more than 6 $M_\odot$. Accretion takes place via the focused stellar wind of the supergiant, generating intense and variable X-ray emission. After its discovery it was remarked that its peculiar spectrum extending in the hard X-ray range with a rather flat power law slope (photon index $\alpha \approx$ 1.5-2.0) and an exponential decay at energies $>$ 50-100 keV, was remarkably different from the spectra of neutron star binary systems, and could not be explained by thermal models, in particular by those describing optically thick disks. This emission is generally interpreted as due to repeated inverse Compton scattering (Comptonization) of soft photons by the thermal energetic electrons of a hot (kT $\approx$ 50-100 keV) cloud (or corona) with typical scattering optical depth $\tau \approx 1$. Sunyaev & Titarchuk (1980) described the emergent spectrum in the approximation of $\tau > 1$ and kT$<<$ mc^2, while later Titarchuck (1994) provided analytical expressions for relativistic case and larger range of kT and τ. Observations by ART-P and SIGMA/GRANAT of Cyg X−1 spectrum in the range 3-300 keV indeed showed the limitation of the Sunyaev & Titarchuk

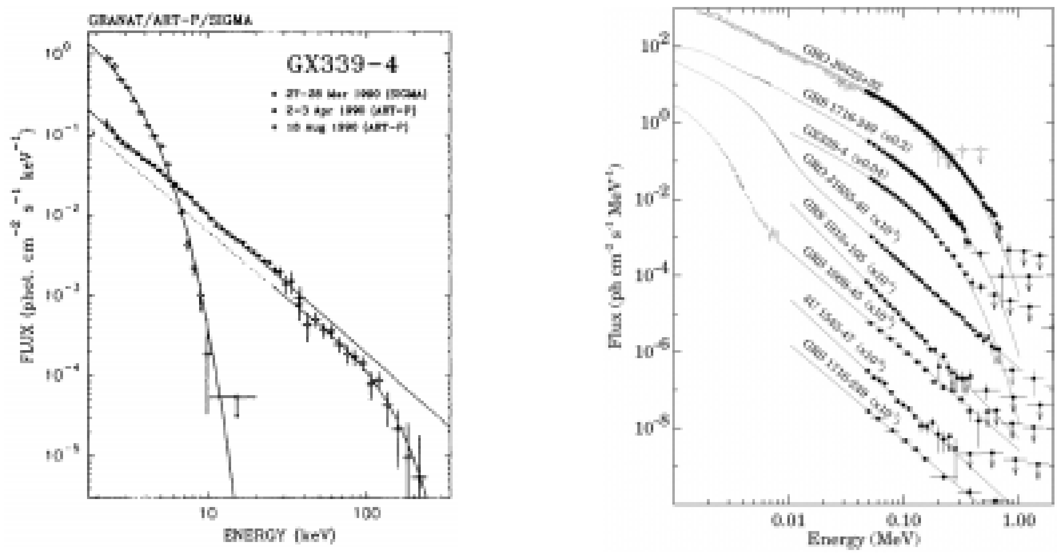

Figure 1: GRANAT/SIGMA-ARTP spectrum of GX 339-4 (from Grebenev et al. 1993) (left). Combined ASCA, TTM, HEXE and Compton-GRO spectra of GBH (from Grove et al. 1998) (left).

(1980) approximation (Grebenev et al. 1993) but the data could still be fitted with more realistic approximations of the Comptonization model.

Cyg X−1 also occasionally shows a different spectrum which is dominated by a strong ultra-soft thermal component which peaks at energies < 1-2 keV and which is generally interpreted as the multicolor black body emission from a geometrically thin and optically thick disk as described by Shakura & Sunyaev (1973). In this spectral state, the power law component is much weaker and steeper ($\alpha \approx 2.5$-3.0) and in some cases absent. In general the variable soft component is found to be anticorrelated to the hard component.

The standard interpretation of these spectra is that the seed photons of the Comptonization come from the disk and, when the accretion rate increases, the emission from the disk also increases, generating the soft thermal component. The large soft photon flux cools down by Compton scattering the hot cloud and quenches the hard component. In the last ten years these two different spectra have been observed in many other BH systems (e.g. Grebenev et al. 1993, Grove et al. 1998, Fig. 1) and infact detection of these two spectral components can be used to identify accreting binaries which probably contain a BH rather than a NS. In spite of the fact that NS binaries show occasionally hard tails or soft components, in general we now know how to recognize BH from from their high energy spectra. The large amount of data collected from these sources have also allowed to characterize their spectral/variability states and the open questions now concern the physical origin and transitions of these states.

3 Black Hole Spectral States, State Transitions and Fast Variability

Five canonical states have been identified in BH binaries: the Very High State (VHS), High/Soft State (HS), Intermediate State (IS), Low/Hard State (LS) and Quiescence State (van der Klis 1995, Mendez et al. 1999). These states are characterized by different combination of the ultra-soft, hard and reflection (continuum excess, fluorescence lines and K-edge) components (Fig. 2 left) coupled to different properties of variability and QPOs (Fig. 2 right). The HS is characterized by the strong ultra-soft thermal component along with a very weak and steep (or even absent) power-law extending to high energies. The spectrum of the LS is instead dominated by the hard power law with exponential cut-off as described above. The VHS resembles the HS where the hard component, though steep, is bright (Fig. 1 right) and it extends to high energies

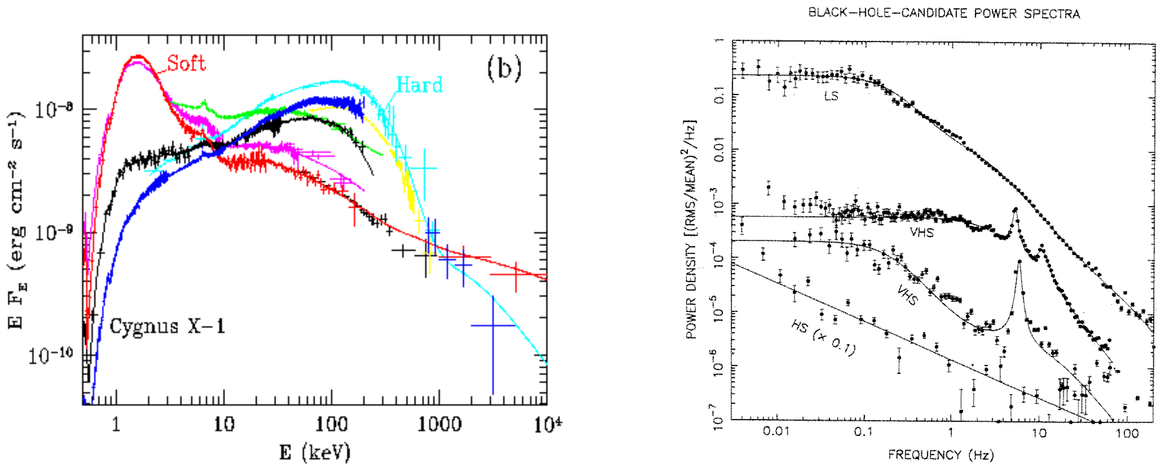

Figure 2: Broad-band spectra of Cyg X−1 in different spectral states (from Gierlinski et al. 1997, 1999) (left). Power spectral density of GBH candidates in different spectral states. From top to bottom: Cyg X−1 in HS, Musca XN in VHS, IS and HS. (from van der Klis 1995) (right).

without evidence of clear exponential break up to > 200-300 keV. The IS is similar to the VHS (both soft and hard component are present) but with a much lower level of emission. Quiescent state is observed in XNs and it is characterized by a very low luminosity ($< 10^{33}$ erg s^{-1}).

During this phase, material is transferred from the companion at a very low rate and it is stored in a low-viscosity accretion disk, without effective accretion into the compact object. The XN outburst is probably initiated by a thermal instability which suddenly produces the fall of the matter accumulated into the disk during quiescence. The effective accretion rate rises to a maximum in few days and decreases over several weeks (often with exponential law) spanning several orders of magnitudes. Thus XN experience different accretion rates and they are often seen over a period of a month or two, to display the different GBH states described above. At the onset of a XN outburst the hard X-rays usually reach the maximum first and then the soft-component develops, the XN enters the very high state, the high/soft state and tends to evolve into the intermediate and the low/hard states before entering again the quiescence phase. The sequence of states seems driven by the accretion rate variation. However, this pattern is not always followed, for example some, even very bright, X-ray Novae have been observed throughout the whole outburst in low/hard state only (e.g. GRO J0422+32 and GRS 1716-249, Fig. 1).

In addition to long term variations, GBH also show rapid aperiodic variability on timescales from several hundred seconds down to milliseconds. BH spectral states are also associated to the specific properties of the fast variability, which is generally described by the power spectral density (PSD) (Fig. 2 right) (van der Klis 1995). In the HS the GBH PSD show a large level of variability (20-35 % rms), with flat slope (red noise) at low frequencies up to a break frequency ν_B ($\approx$ 0.1-1 Hz) and with a power-law slope of index ≈ -1 (flickering) at higher ν. In the HS the level of variability is very low (< 5%) and the PSD has a steep power-law slope. In VHS (and IS) two kind of power spectra are observed one similar to the LS but with lower level of integrated rms (< 15-20 %) and with $\nu_B > 1$ Hz, the other spectrum rather similar to the HS PSD. Features in the PSD, or quasi periodic oscillations (QPO), have also been detected in GBH. Broad QPOs, sometimes referred as peaked noise, are seen at low frequency (< 1 Hz) in LHs, while strong and narrow QPO are observed between 1-10 Hz in VHS. Characteristic times (ν_B, ν_{QPO}) and level of noise seem to vary with source intensity, photon energies and in correlation between them. One important feature which is generally observed is that hard photons lag soft photons with typical time lags of milliseconds-seconds. While the Comptonization can explain in principle the lags, the observed dependency of the lags with frequency requires non homogeneous Comptonizing clouds. The physical link between spectral state and observed variability in BH binaries in still not understood, in spite of the remarkable progresses obtained in the recent past thanks in particular to RXTE results, and the relative succes of shot noise models to interpret the observed PSD (Poutanen et al. 2001).

4 Models and High Energy Tails

Different models of accretion flows have been proposed to account for the BH spectra and their state transitions (see e.g. Liang 1998). They differ mainly on the origin and geometry of the comptonizing plasma producing the hard component. One popular scenario is that the optically thick accretion disk extends down to a critical radius which depends on the accretion rate. For rates of the order of the Eddington limit the disk extends down to the marginally stable orbit, the emission from the disk is intense, peaks at energies of ≈ 1 keV and cools the inner hot cloud (HS). At low accretion rates, the disk is truncated at large radii and the plasma flow becomes geometrically thick (an internal torus or quasi-spherical cloud) hot and optically thin in the inner region. The disk emission decreases and the peak shifts towards lower energies. This hot plasma Comptonizes the disk photons and produces the hard component of the LS. Stable hydrodinamical solutions for such a hot flows have been found for low value of the accretion rate, the so called advection dominated accretion flow (ADAF) models, and they have been employed to describe BH state transitions using the mass accretion rate as basic parameter (Esin et al. 1998). The optically thick disk also reflects the hard photons and give rise to the reflection component more visible during HS but also present in LS (Gierlinski et al. 1997, 1999). The reflection component shows a hump around 30 keV, Fe fluorescence line and K-edge feature around 6-8 keV. Correlation between reflection and hard component slope, ν_B and presence of soft component may support the view that reflection is due to the disk view by a inner hot cloud (Gilfanov et al. 1999) and variations are linked to a change in the internal disk radius. However there is not full agreement on this correlation, the VHS does not fit very clearly in this picture as well as the fact that several XN are seen only in LS, even at high luminosities.

Alternative models propose that the hot cloud is rather a corona envelopping the disk. A uniform corona however is ruled out by the relative low level of reflection, and solutions involving patchy or evaporating coronae have been recently proposed (e.g. Malzac et al. 2002). Another model considers the two basic spectral components arising from two distinct flows, one the standard Keplerian disk the other a sub-Keplerian flow heated by shocks within the flow (e.g. at the centrifugal barrier) (Chakrabarti & Titarchuk 1995). In any case several important questions on geometry of the flow (hot inner cloud or corona), hydrodinamics/heating processes (viscous dissipation or magnetic reconnections) and radiation mechanisms (pure thermal or non-thermal processes) remain open (see reviews by Liang 1998, Zdziarski 2000).

Of particular relevance is the problem of the origin of the hard tail during HS or VHS, when the slope of this component is softer than during LS and does not show high energy cut off. One possibility is that the Bulk Motion Comptonization (BMC) of disk low-energy X-rays by free-falling electrons very close to the BH horizon is the dominant mechanism of this steep hard tail during HS (Laurent & Titarchuk 1999). BMC model predicts correctly the power-law slope but also a high-energy cut off ($>$ 100-300 keV) which has not been observed yet. In particular, it has been recently repoted a detailed study of all CGRO data concerning Cyg X$-$1 in HS from which it appears that the source is clearly detected in the energy bands 1-3 MeV and 3-10 MeV, with fluxes compatible with simple extension of the power-law at 10 MeV (Mc Connel et al. 2002, Fig. 3 left). A competitive model to the BMC is the hybrid thermal/non-thermal model (Zdziarski 2000) which ascribes instead this tail to emission from an additional non-thermal population of electrons.

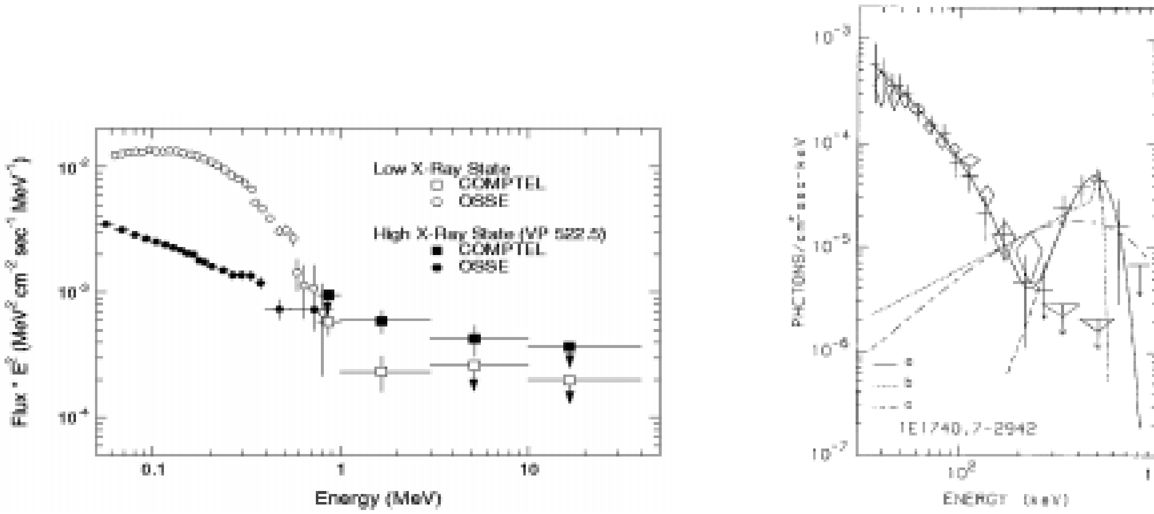

Figure 3: High energy Compton-GRO spectrum of Cyg X−1 (from Mc Connel et al. 2002) (left). Spectrum of 1E 1740.7-2942 during the detection of the high energy feature (Bouchet et al. 1992) (right).

Even if the LS hard component seems well explained by thermal Comptonization plus a reflection component, a contribution from non-thermal population has also been considered. Indeed the recent compilation of Comptel/CGRO high energy data on Cyg X−1 by Mc Connel et al. (2002) seems to indicate the presence of a hard component at > 600 keV, sticking out from the thermal exponential tail, observed from the source in LS. A similar result was obtained with SIGMA and with Compton/GRO data also on the bright XN GRO J0420+32, which was in LS throughout its entire outburst (Roques et al. 1994).

A recent issue connected with the detections of high energy tails is the observed correlation of the LS hard component with radio emission interpreted as thick synchrotron radiation from the base of jets in the source. Recent multi-wavelength observations of BH X-ray binaries, as e.g. for XTE J1550-564, have shown clear presence of flat-spectrum radio emission when they are in low state with positive correlation of the intensities. This suggests a coupling between radio jets and Comptonization, and possibly contribution by the accelerated electrons to X-ray emission via inverse Compton or even synchrotron processes (Fender 2001).

5 High Energy Emission Features in GBH

Apart from the persistent high energy tails a number of detections of variable high energy "features" at > 300 keV, sticking out from the simple extrapolation of the continuum emission of GBH have been reported. They obviously have attracted interest because of their possible link with electron-positron annihilation, pair plasma and non-thermal radiation processes.

The 1 MeV bump of Cyg X-1 observed with HEAO-3 (Ling et al. 1987) was the first significant report of such events. The feature appeared when Cyg X−1 was in its standard hard state during a low level of gamma-ray emission (the $\gamma 1$ state). The excess was observed during 14 days in the range 400 keV - 1.5 MeV. The feature was never detected again. On the other hand it was recently reported the detection of a gamma-ray transient burst of 10 ks duration, with Ulysses and Konus-Wind from a direction compatible with the Cyg X−1 position (Golenetskii et al., IAUC 7840).

A broad emission feature in the 300-700 keV band was detected with the SIGMA/GRANAT telescope in automn 1990 from the hard X-ray source and microquasar 1E 1740.7-2942 (Bouchet et al. 1992). The feature was observed for 1 day at a level of > 6 σ, could be fitted with a large Gaussian line, and was not compatible with a narrow 511 keV line even associated to positronium emission (Fig. 3 right). The excess was not present during the observations performed 3 days before and the day after the event. A following detection during fall 1991 at much lower significance level (4 σ) (Cordier et al. 1993) was not confirmed by simultaneous Compton GRO observations.

Another remarkable result obtained with the soft gamma-ray SIGMA/GRANAT telescope was the detection of a high energy variable line feature from the X-Ray Nova Muscae 1991 (GRS 1124-684), a dynamically proven BH, during its main outburst. The emission line was centered at 480 keV with flux of 6 10^{-3} ph cm^{-2} s^{-1} and width of 23 keV, compatible with instrument resolution (Goldwurm et al. 1992) (Fig. 4). The variable line was seen few days after the XN reached the peak of bolometric luminosity when the source was in VHS for about 20 hours. Initially interpreted as red-shifted annihilation line, many unresolved issues about the possible site of annihilation and positron production mechanism remain. The positrons could have been formed in the inner hot part of the accretion disk and then have annihilated in a colder medium, for example in the external part of the disk. However the red-shift would imply an annihilation site very close to the BH and the line should be larger due to Keplerian rotation and to higher temperatures. Moreover if the positrons are produced by γ-γ interactions, with $>$ 511 keV γ-rays from a hot pair plasma or within a jet, an intense $>$ 500 keV continuum component should have also been observed. A number of models were proposed in this frame, and recently Kaiser and Hannikainen (2002), making a correlation with the radio flare which intervened few days after, proposed that the line is produced within a jet and the frequency shift is due to doppler effect.

A second feature at $\approx$ 200 keV seems also present in the spectrum and was interpreted as backscattering of 511 keV from the disk edge (Hua & Lingenfelter 1993) or as result of distorsion of the 511 keV line in a Keplerian disk around a BH (Hameury et al 1994). A different interpretation was proposed when relevant amount of Li was discovered in the secondaries of BH XN. Martin et al (1996) proposed that 478 keV line could arise from decay of excited ^{7}Li produced in α-α reactions directly or from Be decay obtained in spallation processes during the outburst. Certainly suggestive, this view encounters difficulties because this mechanism would also generate excited ^{7}Be which would produce a line at 430 keV with similar intensity, therefore combined 478 and 430 lines would not be so narrow for NaI scintillators instruments like SIGMA. Guessoum & Kazanas (1999), re-discussing a scenario of Li production in hot ADAF proposed by Yi and Narayan (1997) and in general in nucleosynthesis processes in accretion flows around BH, found that Li would be depleted by proton collisions or photodissociation in the hot flow and would not provide detectable fluxes. On the other hand they investigated production of 2.223 MeV gamma-ray line from neutron capture by protons, due to the large neutron fluxes obtained in the hot accretion flows intercepting the secondary.

In any case transient high-energy emission lines of such intensities remain rare events, since neither SIGMA nor CGRO ever detected such features in other X-Ray Novae (Goldoni et al. 1999, Grove et al. 1998, Cheng et al. 1998), even if these results may be due to the non complete coverage of XN in VHS close to peak activity. Upper limits on high energy lines from GBH reported from CGRO data are of the order of 5-15 10^{-4} ph cm^{-2} s^{-1} for one day of data integration.

6 New Results and Perspectives

Other recent results obtained in particular with RXTE, Beppo-SAX, Chandra and XMM-Newton, show however that the standard picture and in particular the assumption that state transitions are driven by accretion rate changes, is not fully compatible with the data.

One new important finding of the last years was the discovery with RXTE of high frequency (60 - 450 Hz) QPO in GBH and in particular in the two superluminal microquasars

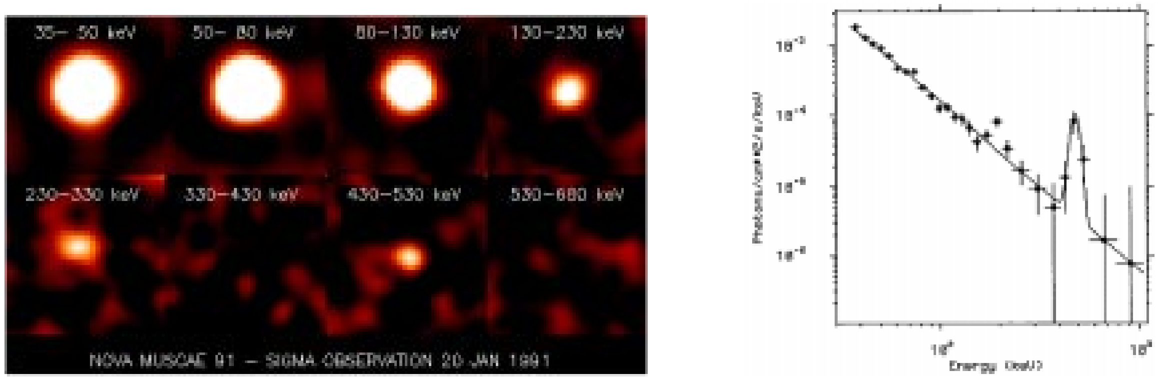

Figure 4: Gamma-Ray images in different energy bands of the X-Ray Nova Muscae recorded by the SIGMA/GRANAT telescope on 20 Jan 1991 (left). The image in the 430-530 keV band shows a significant excess at the source position while no signal is found in the lower energy one. The corresponding photon spectrum of the source fitted with a power-law and a Gaussian line (from Goldwurm et al. 1992) (right).

GRS 1915+105 and GRO 1655-40 (Strohmayer 2001). The involved timescales imply emission site very close to the BH horizon and therefore pose strong constraints on the radiation mechanisms and possibly on BH spin and mass of the system (Greiner et al. 2001).

Observations of XN XTE 1550-564 have showns that the source changed state on timescale of days and weeks with no clear correlation with accretion rate (Homan et al. 2001). The authors conclude on this basis and other indications that at least another independent parameter, in addition to mass accretion rate, drives the state transitions in GBH systems.

Another important recent result is the detection of a peculiar low/soft state in the persistent GBH and microquasar GRS 1758-258 (Smith et al. 2001, Miller et al. 2002, Goldoni et al. 2002, Goldwurm et al. 2002) and the fact that in this source, differently than for Cyg X−1, the spectral changes seem correlated to flux changes rather then being correlated to intensity itself.

All these results open new questions regarding the physics involved in GBH which definitely require further studies and deeper high energy broad band observations. INTEGRAL, thanks its broad band sensitive range (3 keV - 10 MeV) large sensitivity and spectral/imaging capabilitites will provide new deep insight in the domain of the astrophysics of black hole systems. The persistent GBH and the transient GBH are indeed major target for the mission and we expect that important results will be obtained from the INTEGRAL observation program of these objects, in particular if correlated to multiwavelength observation programs involving soft X-rays, radio, optical/IR telescopes.

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